

Origins of Solar System Dust Beyond Jupiter

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ABSTRACT

The measurements of cosmic interplanetary dust by the instruments on board the Pioneer 10 and 11 spacecraft contain the dynamical signature of dust generated by Edgeworth-Kuiper Belt objects, as well as short period Oort Cloud comets and short period Jupiter family comets. While the dust concentration detected between Jupiter and Saturn is mainly due to the cometary components, the dust outside Saturn's orbit is dominated by grains originating from the Edgeworth-Kuiper Belt. In order to sustain a dust concentration that accounts for the Pioneer measurements, short period external Jupiter family comets, on orbits similar to comet 29P/Schwassmann-Wachmann-1, have to produce $8 \times 10^4 \text{ g s}^{-1}$ of dust grains with sizes between 0.01 and 6 mm. A sustained production rate of $3 \times 10^5 \text{ g s}^{-1}$ has to be provided by short period Oort cloud comets on 1P/Halley-like orbits. The comets can not, however, account for the dust flux measured outside Saturn's orbit. The measurements there can only be explained by a generation of dust grains in the Edgeworth-Kuiper belt by mutual collisions of the source objects and by impacts of interstellar dust grains onto the objects' surfaces. These processes have to release in total $5 \times 10^7 \text{ g s}^{-1}$ of dust from the Edgeworth Kuiper belt objects in order to account for the amount of dust found by Pioneer beyond Saturn, making the Edgeworth-Kuiper disk the brightest extended feature of the Solar System when observed from afar.

Subject headings: solar system: dust, Kuiper belt, comets: individual (1P/Halley, 29P/Schwassmann-Wachmann 1), in situ measurements: Pioneer 10/11

1. Introduction

Our Solar System as well as other planetary systems is filled with small solid particles, either interstellar survivors of the formation process, or fragments of larger bodies like asteroids, comets, moons, or planets. Commonly referred to as interplanetary dust, these particles carry information about their sources, not only by their chemical signature (??), but also by the size and shape of their orbits around the Sun. The particles' chemistry as well as their orbit can best be gauged in situ, that is by dust detectors on board interplanetary spacecraft. While the accretion of interplanetary dust particles by the Earth's atmosphere allows their mineralogical, chemical, and isotopic analy-

sis in ground-based laboratories after their collection by high-flying aircraft, information on their orbit around the Sun is lost after the atmospheric entry. The orbital properties of Solar System dust inside Jupiter's orbit has been extensively studied by in situ measurements (?????). From these measurements Jupiter family short period comets and asteroids have been identified as the dominant dust sources (??). In the grain size regime below $1 \mu\text{m}$ a high abundance of interstellar grains was found (?). While interstellar impactors can easily be distinguished from detections caused by solar system dust, it is still unclear what the relative contribution of the various interplanetary sources is. Besides this uncertainty, the large number of in situ measurements taken inside Jupiter's orbit led to a consistent picture of the extend and distribution solar system dust cloud there. The situation beyond Jupiter's orbit is however vastly different. So far the only in situ dust detectors ever to fly beyond Jupiter are the dust experiments on board

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the Pioneer 10 and 11 spacecraft (?)⁵. Measurements of the plasma instruments on board Voyager 1 and 2 seem to indicate a high concentration of micron-sized particles out to 50 AU (?). The Voyager results are however not conclusive because the plasma instruments have never been calibrated to measure dust impacts. From the Pioneer 10 and 11 measurements (?) found that, taken as an ensemble, the particles have to have a constant spatial concentration as function of the distance from the Sun and move on highly eccentric, randomly oriented orbits. In this report we use the Pioneer 10 and 11 data to identify the source objects of the particles by modelling the sources' signature in the Pioneer data, and comparing the measurements with the result of the modelling.

2. In situ Measurements beyond Jupiter by the Pioneer Missions

The Pioneer instruments consist of panels of 234 pressurised cells, mounted on the back of the spacecraft's high gain antenna. The cells are divided in two separate electronic channels for redundancy, 108 cells are connected to channel 0 and 126 cells are connected to channel 1. Each cell has a cross section area of $2.45 \times 10^{-3} \text{ m}^2$. The instruments register the time when a particle penetrates the thin wall of the cell that encloses the pressurised gas. Before the penetration the gas acts as an insulator between two electrodes, and as it escapes into the vacuum of space, the electrodes discharge and the resulting electrical signal is registered as a penetration event. The sensitivity of the instrument, that is the minimum impact mass and velocity that causes a penetration, is determined by the thickness of the cell walls. On the Pioneer 10 experiment walls of $25 \mu\text{m}$ were used, and on Pioneer 11 the cell walls were $50 \mu\text{m}$ thick. At a typical impact velocity of 20 km s^{-1} , the Pioneer 10 cells are penetrated by particles with an equivalent diameter larger than $10 \mu\text{m}$, and the Pioneer 11 cells are penetrated by $21 \mu\text{m}$ particles (?)⁶. The surfaces of the Pioneer instruments always point nearly opposite to the high gain antenna, away from the Earth. Beyond Jupiter this means the instruments are oriented mainly away

from the Sun with an effective field of view of $1.6\pi \text{ sr}$ (240° opening angle). The Pioneer 10 instrument took measurements from the launch on 2 March 1972 until it failed on 10 May 1980 due to the low temperatures, 18 AU from the Sun (for the geometry of the spacecraft trajectories see figure 1). Pioneer 11 performed dust measurements from launch on 5 April 1973 until it was switched off 25 September 1983. The Pioneer dust instruments successfully detected 225 penetrations altogether, however, they did not work flawlessly. On Pioneer 10 one channel failed completely, and on Pioneer 11 an unexplained discrepancy between the rate of penetrations measured by both channels was observed. The flux measured by one channel of the Pioneer 11 instrument is consistently higher than the flux measured by the other. Because the angular sensitivity of both channels is identical, this discrepancy can only be due to a malfunction of one of the channels. Despite these inconsistencies we consider the Pioneer dust data to be reliable for the following reasons: (a) the rate of detected events increased sharply during the fly-bys of Jupiter and Saturn which is not expected for random noise, and (b) the flux densities measured by Pioneer 10 and 11 at 1 AU are in accord with measurements by Explorer 23, an Earth orbiting spacecraft that was equipped with similar instruments (?). The discrepancy between the Pioneer 11 channels can be explained by either the loss of cells on one of the channels during the launch of the spacecraft, or by electronic noise in one of the channels. Figures 2a and b show the interplanetary penetration flux⁷ on the Pioneer dust instruments as a function of time and distance from the Sun. After the launch the dust flux measured by Pioneer 10 is $2 \times 10^{-5} \text{ m}^{-2} \text{ s}^{-2}$, continuously decreasing with heliocentric distance to $3 \times 10^{-6} \text{ m}^{-2} \text{ s}^{-1}$ at Jupiter distance. After passing Jupiter's orbit, the flux measured by Pioneer 10 stays almost constant. Due to the lower abundance of large grains the fluxes measured by the less sensitive Pioneer 11 instrument are smaller but they draw a similar picture: decreasing flux from Earth to Jupiter, and an almost constant flux outside Jupiter's orbit.

⁵Since 31 December 2000, the Cassini spacecraft is outside Jupiter's orbit on its way to its final destination Saturn.

⁶Assuming a grain mass density of 1 g cm^{-3} .

⁷Penetrations per unit area and time, sliding mean over 4 penetration events, penetrations during the fly-bys of the planets have been removed.

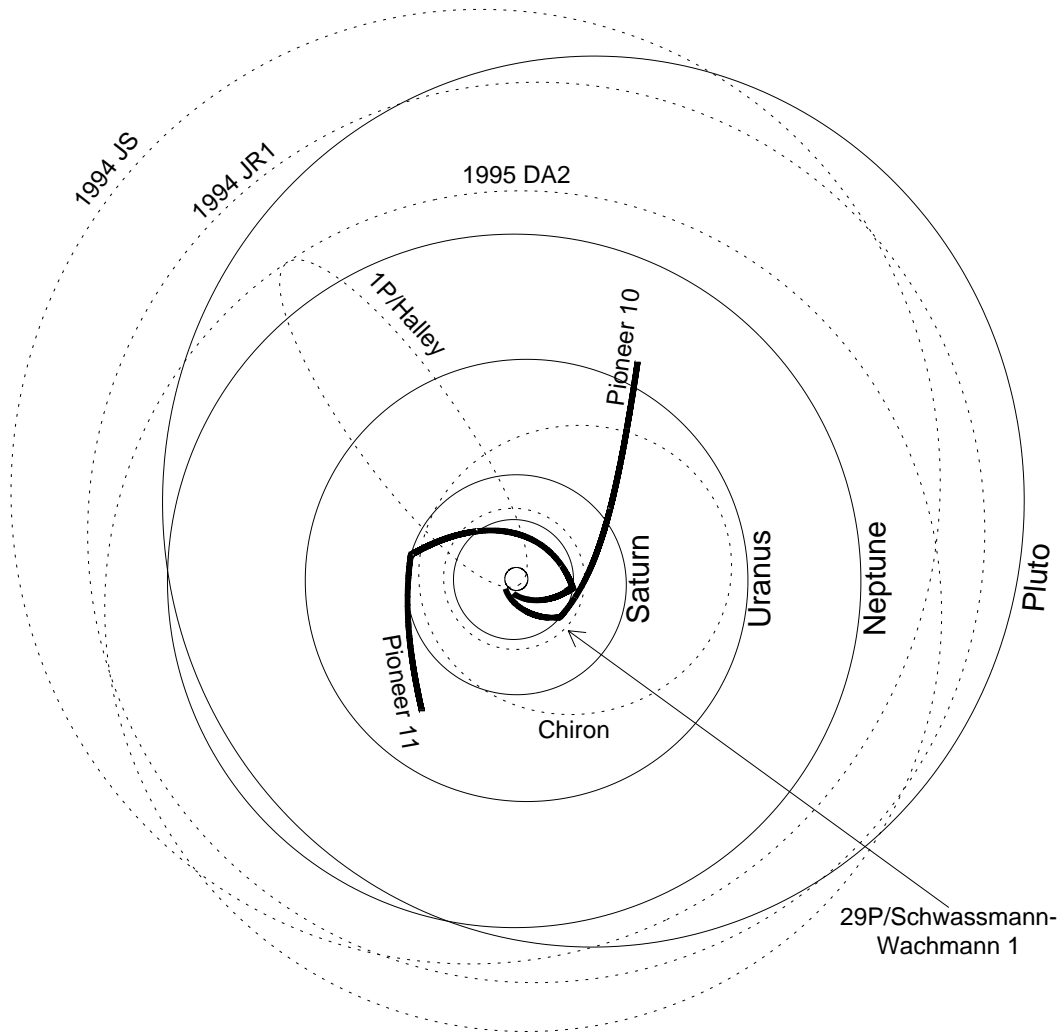


Fig. 1.— Overview of the orbits of the Pioneer spacecraft (solid, thick) and potential dust source objects (dotted). The orbits of the planets Earth, Jupiter, Saturn, Uranus, Neptune, and Pluto are shown as the thin solid lines. As representatives of the dust sources comets 1P/Halley and 29P/Schwassmann-Wachmann 1, the Centaur object 2060 Chiron, and the transneptunian objects 1994 JS, 1994 JR1, and 1995 DA2 are shown.

3. Sources of Dust Beyond Jupiter

What are the sources of the particles that penetrated the cells of the Pioneer dust instruments? The interstellar dust stream that was discovered by the dust instrument on board Ulysses causes an approximately constant dust concentration around the Sun, which potentially explains the constant penetration rate of the Pioneer instrument. However, from the extrapolation of the flux-mass distribution of interstellar dust measured by Ulysses to the Pioneer 10 threshold mass, it follows that less than $10^{-8} \text{ m}^{-2} \text{ s}^{-1}$ interstellar penetrations of Pioneer 10 cells can be expected (?), less than one percent of the measured flux. We are thus left with interplanetary particles as the cause for the penetrations detected by the Pioneer dust experiments. Since the abundance of interplanetary particles decreases steeply with their size (?), we can assume that the penetrations were caused mainly by particles with sizes just above the detection threshold of the instruments, i.e., with diameters in the order of $10 \mu\text{m}$. Particles in this size regime move approximately on Keplerian orbits, because their dynamics are dominated by solar gravity. Over long time scales the orbits evolve under Poynting-Robertson (PR) and solar wind drag. This drag force is caused by the relativistic aberration of the sunlight and solar wind particles (?). The effect of PR and solar wind drag is to remove energy from the particle's orbit causing a slow inward directed spiral motion of the particles. The aphelion of a source object of a particle must therefore be equal or larger than the particle's distance from the Sun. Consequently, the sources of the constant flux of particles measured by Pioneer outside Jupiter must lie beyond Jupiter's orbit. We distinguish 3 dynamic families that we consider as potential dust sources: 1P/Halley-type comets (HTC, short period Oort cloud comets), 29P/Schwassmann-Wachmann-1-type comets (SW1TC, short period Jupiter family comets with perihelion close to Jupiter's orbit), and Edgeworth-Kuiper belt objects (EKBOs). Both, 1P/Halley as well as 29P/Schwassmann Wachmann 1 have been reported to be prolific sources of dust (??) as they disintegrate due to solar heating. For EKBOs it is proposed that they release dust due to mutual collisions (??) and due to impacts by interstellar particles (?). Another potential source of dust outside Jupiter

are Centaur objects that orbit the Sun between Saturn and Uranus. They are however not considered strong sources, because their number is too small to cause frequent collisions, and dust particles released by them are likely to be ejected from the solar system due to their highly eccentric orbits that cross the orbits of several giant planets. They are also too far from the Sun to exhibit a strong cometary activity (?). The dynamic families of source objects described above are defined by their interaction with the major planets. Comets are considered a HTC if their perihelion is inside Jupiter's, their aphelion outside Neptune's orbit, and their inclination between 160° and 180° . SW1TCs have their perihelion close to Jupiter's orbit, an eccentricity below 0.1, and an inclination below 10° . Finally members of the EKBO family have perihelia beyond Neptune, eccentricities below 0.1, and inclinations below 20° , which includes classical as well as scattered members of the Edgeworth-Kuiper belt (?).

4. Dust Distribution by Orbital Evolution

What is the signature of particles from HTCs, SW1TCs, and EKBOs in the Pioneer data? The particles' equilibrium distribution in the solar system is determined by their initial orbit after they have been released from the source object⁸, and by their orbital evolution under PR and solar wind drag, as well as under gravitational perturbations by the planets. The effect of the planet's gravity on the grains is strongest when the orbital period of the planet and the particle have an integer ratio, that is when the particle is in a mean motion resonance (MMR) with the planet. An MMR is described by the ratio $p : q$, where q is the number of orbits the particle completes in the time the planet orbits the Sun p times. The effect of exterior MMRs, for which $p > q$, as well as on the spatial distribution and orbits of dust particles in the solar system has been predicted (?) and observed (?). When a particle is in an exterior MMR, its Sun-ward motion is temporarily halted, because the energy loss due to PR and solar wind drag is compensated by the resonant interaction with the planet's gravity field. But then the eccentricity of the particle's orbit increases until a

⁸Or equivalently from cm-sized fragments that form the source object's trail along its orbit.

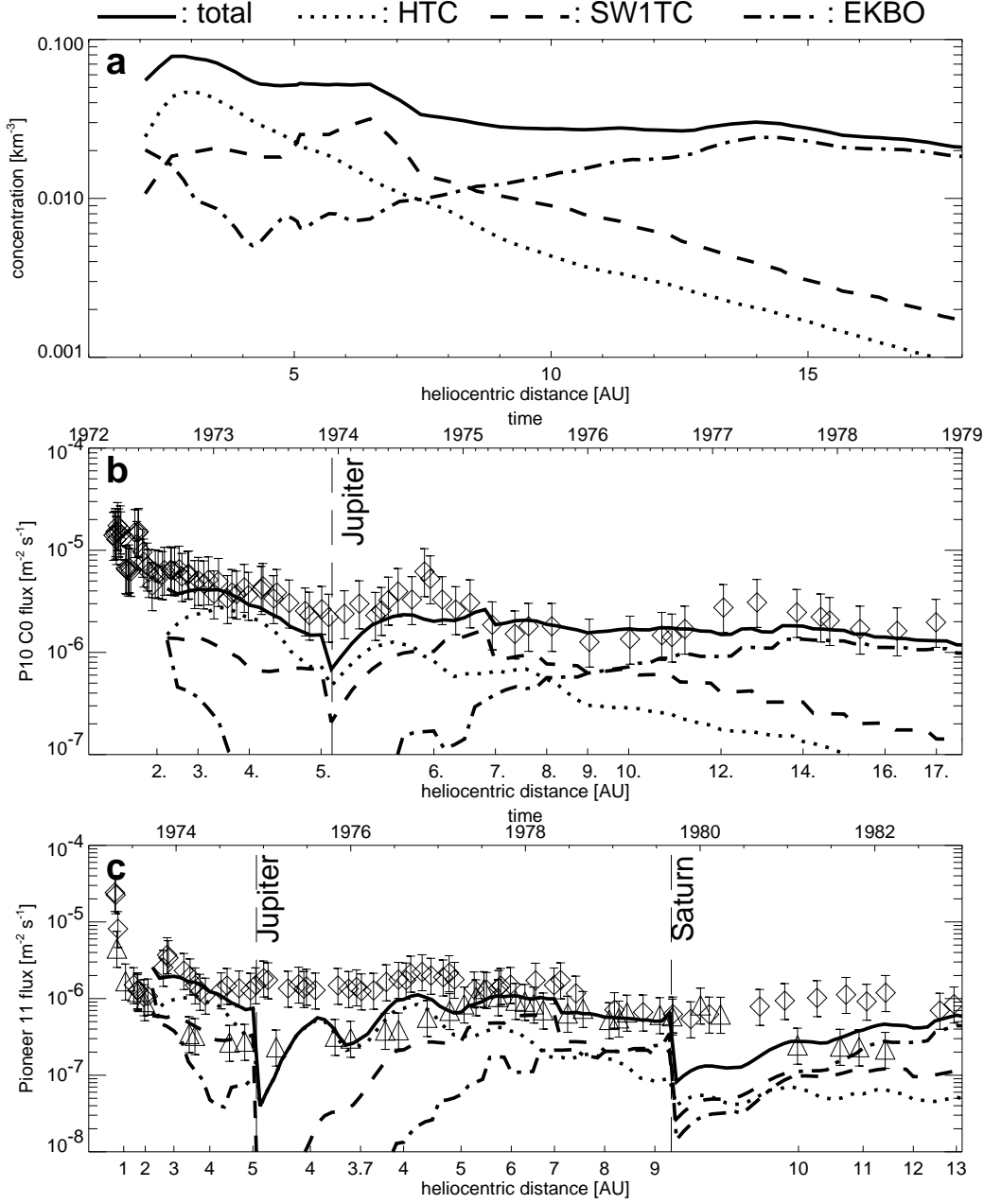


Fig. 2.— Radial profiles of the distribution of interplanetary dust in the outer solar system. The concentration of dust particles from 1P/Halley-type comets (HTC), 29P/Schwassmann-Wachmann-1-type comets (SW1TC), and Edgeworth-Kuiper Belt Objects (EKBO) that is needed to account for the Pioneer 10 measurements is shown in **a**. The comparison **b** of the calculated radial flux signatures of the various sources with the penetration fluxes measured by Pioneer 10 (diamonds, error bars indicating 1σ errors) that particles from HTCs contribute mainly inside Jupiter's orbit, SW1TC particles between 6 and 7 AU, and particles from EKBOs dominate outside 10 AU. The profile of the penetration flux of the Pioneer 11 dust instrument (**c**, diamonds: channel 0 data, triangles: channel 1 data) is very flat due to the triple passage of Pioneer 11 through the 4-to-5-AU region.

close encounter with the resonant or a neighbouring planet ejects the particle from the resonance. Depending on the planet's mass and the proximity of other strong perturbers, the exterior MMRs cause a circumsolar dust ring to form. The equilibrium distribution is achieved when the dust production by the sources is equalised by the particle sinks, which are evaporation close to the Sun and ejection from the solar system by close encounters with the giant planets, mainly Jupiter and Saturn. Due to the long time scales of orbital evolution, the equilibrium distribution is reached after 10^5 to 10^6 years⁹. This means that not a single comet, the lifetime of which is typically 10^3 to 10^4 years, but only a whole class of comets with similar orbital characteristics can sustain a equilibrium distribution. For particles originating from HTC's, it was found (?) that they mainly occupy $p : 1$ MMRs with Jupiter, where p ranges from 2 to 12. When they leave the Jupiter resonances, they continue Sun-ward until they evaporate. Unlike HTC particles, dust particles released by SW1TCs are not concentrated in exterior Jupiter MMRs. This is caused by their unstable initial orbits which bring them close to Jupiter within the first few centuries after their release from the parent comet. Jupiter perturbs SW1TC particles out to Neptune's orbit with the maximum spatial concentration at 5 to 6 AU. Particles originating from EKBOs approach the planets' orbits from the outside and consequently are found mainly in the $2 : 1$, $3 : 2$, or $4 : 3$ resonance with Neptune (?). After they are ejected from the exterior Neptune MMRs, they continue to spiral toward the Jupiter/Saturn region, where 80% of them are ejected from the solar system by close encounters with one of the giant planets. The other 20% continue to spiral Sunward where they evaporate at a solar distance that depends on their composition. Figure 2a shows the radial profile of the spatial particle concentration in the solar system for particles from HTC's, SW1TCs, and EKBOs.

We have simulated the Pioneer 10 and 11 measurements along the spacecraft's orbits by calculating the flux of dust particles from a given source on the target surface of the dust detector at the spacecraft location, given the spacecraft attitude and velocity vector, and the local dust concentra-

tion and velocity vector. Figures 2a and b show the predicted and the measured dust fluxes on the Pioneer 10 and 11 instruments, respectively. Because the average dust production rates of the source objects is unknown, we treated the the total amount of dust, that is the normalisation of the radial concentration profile, as a free parameter that was established by a least-square fit of the predictions to the measured values. On both spacecraft the penetration flux initially decreased due to the lower dust concentration at larger heliocentric distances. The peak in the penetration flux measured by Pioneer 10 end-1974 at 6 AU is well explained with penetrations caused by particles from HTC's and SW1TCs. The peak appears to be even stronger than expected from our calculations. At heliocentric distances of 7 AU and beyond, the constant penetration flux of $2 \times 10^{-6} \text{ m}^{-2} \text{ s}^{-1}$ can only be explained if we include a substantial contribution from EKBO particles. At 18 AU the flux of EKBO particles dominates the other two sources by an order of magnitude. Because the Pioneer 11 dust instrument did not provide much data beyond the Jupiter-Saturn region, the signature from EKBO particles is less dominant. Between Jupiter and Saturn, as well as between Saturn's orbit and a heliocentric distance of 11 AU, the contributions from all three sources are comparable.

5. Dust Production Rates

The comparison of the measured fluxes with the calculated radial profiles gives us a direct determination of the dust particle production rates. In order to provide the penetration fluxes shown in figure 2a, HTC's have to produce 6×10^{11} , SW1TCs 3×10^{11} , and EKBOs 2×10^{14} dust particles of size $10 \mu\text{m}$ and larger per second. The production rate in terms of dust mass is given by the integral of the production rate over the grain mass distribution. The integration covers grain masses from the lower sensitivity limit of the Pioneer 10 instrument of 10^{-9} g to an upper limit of 0.1 g . The lower mass limit of HTC grains is 10^{-7} g , because the high eccentricity of the source object and solar radiation pressure cause them to leave the Solar System if they have smaller masses. The upper limit is determined by the requirement that the grains have to be distributed by orbital evolution over a large volume in order to contribute to the interplanetary dust flux measured by Pioneer. Only grains

⁹For dust particles with sizes in the order of $10 \mu\text{m}$.

with masses of less than 0.1g move away from their parent body's orbits on times scales shorter than the age of the Solar System. Assuming a generic collision-type grain mass distribution (?), we find dust mass production rates of $3 \times 10^5 \text{ g s}^{-1}$ for HTC's, $8 \times 10^4 \text{ g s}^{-1}$ for SW1TC's, and $5 \times 10^7 \text{ g s}^{-1}$ for EKBO's.

6. Discussion

From in situ measurements (?) as well as remote sensing experiments (?) close to the comet's perihelion it was found that 1P/Halley's dust production rate during its active phase was 10^7 g s^{-1} . Keeping in mind that comet 1P/Halley has an active period that covers less than 1% of its orbital period, we find that Halley itself produces on average less than 10^5 g s^{-1} . This means that, unless HTC's have been much more active in the past, there must be a significant contribution from other sources, like short period Jupiter family comets, in order to sustain the dust concentration observed by Pioneer 10 between 2 and 5 AU. The measurements by Pioneer 10 at heliocentric distances larger than 6 AU provide better constraints on the dust production rate of SW1TC's than on the dust production by HTC's. The high penetration flux measured between 6 and 7 AU can not be explained with a contribution from HTC's or short period Jupiter family comets. From the Pioneer 10 measurements we find that, on average, $8 \times 10^4 \text{ g s}^{-1}$ of dust have to be generated by SW1TC's. This is considerably lower than the value of $(6 \pm 3) \times 10^5 \text{ g s}^{-1}$ for the current dust production rate found by (?) for 29P/Schwassmann-Wachmann 1 itself. This confirms that, due to the proximity of the strong perturber Jupiter, the dwell time of SW1TC's in their peculiar orbits is small compared to their lifetimes. This also means that 29P/Schwassmann-Wachmann 1 itself is able to provide a major fraction of solar system dust that is currently found between 6 and 8 AU.

Our calculations show that the interplanetary dust environment outside Saturn is dominated by particles originating from EKBO's, unless there is an unexpected significant contribution from Centaur objects or unknown sources. If there were a significant amount of dust from Centaur objects, its spatial density would decrease steeply with increasing heliocentric distances due to the high ec-

centricity of the Centaurs' orbits. Such a radial distribution would not explain the nearly constant flux observed by Pioneer 10 outside Saturn's orbit. In order to fit the Pioneer 10 detections outside 10 AU, dust has to be produced in the Edgeworth-Kuiper belt at a rate of $5 \times 10^7 \text{ g s}^{-1}$. Because we assume an equilibrium dust distribution, this value represents the average over the typical dust particle lifetime of 10^7 years. Estimates of the collisional dust production (?), that include up to kilometre-sized fragments, give values of 10^9 to 10^{11} g s^{-1} . However, the orbits of these large fragments do not evolve under PR drag into the 10 to 18 AU region. Translating the collisional production rate into the mass range between 10^{-9} and 0.1g gives a value between 9×10^5 and $3 \times 10^8 \text{ g s}^{-1}$, depending on the surface properties of EKBO's. In addition to the collisional dust production, the production of particles by impacts of interstellar dust grains onto EKBO's was found to be between 3×10^5 and $3 \times 10^7 \text{ g s}^{-1}$ (?). Thus, the EKBO dust production rate derived from the Pioneer 10 measurements is on the high side of the source models, but well within the theoretical uncertainties, which include the size distribution of Edgeworth-Kuiper belt objects, the impactor flux, and the source objects' surface properties.

7. Conclusion

The discussion above shows that we have been able to identify a set of observable dust sources for the Pioneer dust measurements. Unlike the interpretation by (?), we have used a set of 3 dynamical families of source objects. The sum of these sources provides the right spatial and local velocity distribution that explains the penetration fluxes measured by Pioneer. We found the calculated signature of the source families in the data to be independent, that is dominant for different heliocentric distances, so that dust production rates for the individual sources could be derived separately from the data. Especially the data collected by the spacecraft outside Saturn's orbit is very valuable, because with increasing heliocentric distance the number of possible contributors to the interplanetary dust cloud decreases. The only known source of interplanetary dust outside Saturn is the Edgeworth-Kuiper belt. This gives us the opportunity to unambiguously determine the amount of dust released by the objects of the

belt. According to the Pioneer 10 measurements, the density of interplanetary dust generated by the Edgeworth-Kuiper belt is high enough so that this dust cloud is the second brightest feature of the solar system when observed from afar (?). Thus the Edgeworth-Kuiper belt and the distribution of dust particles it produces can act as a model for detecting other planetary systems around mid-age main sequence stars. Interplanetary dust in the region between Jupiter and Saturn gives us information about the dynamical properties of this interesting region. Since a fly-by of Jupiter on 31 December 2000 the Cassini spacecraft is on-route to Saturn, carrying a highly sensitive dust instrument. It will provide data on the mass, velocity, and chemical composition of the smaller sized dust particles.

8. Acknowledgements

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